Molecular Diversity (2005) 9: 277–290
DOI: 10.1007/s11030-005-8112-3

Full-length paper

Cinchona alkaloid-based polymer-bound phase-transfer catalysts: Efficient enantioselective alkylation of benzophenone imine of glycine esters

Baptiste Thierry, Jean-Christophe Plaquevent & Dominique Cahard*
UMR 6014 CNRS de l'Institut de Recherche en Chimie Organique Fine (IRCOF), Université de Rouen, 1 Rue Tesnière, 76821 Mont Saint Aignan Cedex, France
*(*Author for correspondence, E-mail: dominique.cahard@univ-rouen.fr)*

Received 13 September 2004; Accepted 29 November 2004

Key words: amino acids, asymmetric catalysis, cinchona alkaloids, phase-transfer catalysis, polymers

Summary

Cross-linked polystyrene-bound and poly(ethylene glycol)-bound phase-transfer catalysts as well as homopolymers of cinchona alkaloid derivatives have been synthesised. Both soluble and insoluble polymers have been investigated. The enantioselective alkylation of *N*-diphenyl methylene glycine *t*-butyl ester has been successfully carried out in heterogeneous and homogeneous systems. High enantioselectivities (up to 96%) have been obtained. The polymer-bound catalysts have been easily recovered and conditions for efficient recycling have been studied.

Introduction

O'Donnell first introduced the asymmetric synthesis of α-amino acids under phase-transfer catalysis in 1989 [1]. The liquid/liquid phase-transfer catalysed asymmetric alkylation of *N*-diphenyl methylene glycine *t*-butyl ester with the aid of *N*-benzyl cinchona alkaloid chlorides **1** (Figure 1) provided the α-alkyl-α-amino acids with up to 66% ee. The same group further developed this reaction; they introduced the *N*-benzyl-*O*-allyl cinchona alkaloid bromides **2** (Figure 1) as improved catalysts allowing to reach up to 81% ee [2]. Finally, in 1997, Corey [3] and Lygo [4] independently reported highly efficient phase-transfer catalysts **3** and **4** (Figure 1) which incorporate a sterically hindered *N*-methyl anthracenyl moiety as a powerful unit for masking the nitrogen face and leading to substantially improved ee's (up to 99.5%).

Other approaches recently emerged as efficient variants in the alkylation of *N*-diphenyl methylene glycine *t*-butyl ester: dimeric [5], trimeric [6], and dentritic [7] cinchona alkaloid-derived ammonium salts, guanidinium salts [8], C_2-symmetric chiral quaternary ammonium salts [9], other ammonium salts [10], and metal catalysts [11]. The cinchona alkaloids are natural products that possess several important features (relatively inexpensive, stable, available as diastereomeric pairs allowing the access of both enantiomers of the products, easy structural modifications) which render them attractive as asymmetric organocatalysts [12]. We thought that a further useful development in the field of asymmetric synthesis of α-amino acids under phase-transfer catalysis would be the immobilisation of the cinchona alkaloid-based catalysts on a polymeric support. The development of recoverable and recyclable reagents supported on diverse polymeric matrixes is a valuable approach which offers several advantages: the ease of physical separation of the polymer, the facilitated product purification, and the potential recycling [13]. We herein describe the synthesis of polymer-bound cinchona ammonium salts using insoluble and soluble polystyrene matrixes, homopolymers of *O*-9-(4-vinylbenzoyl ester) of cinchona alkaloids and poly(ethylene glycol) supports. The evaluation of their catalytic asymmetric behavior in the phase-transfer alkylation of glycine derivatives has been conducted and the recycling of some polymeric organocatalysts has been studied.

Results and discussion

There are many examples of enantioselective reactions in which polymer-bound cinchona alkaloids were used as catalysts: for example, the Michael addition [14], the Sharpless dihydroxylation [15], the epoxidation of chalcone [16], the nucleophilic addition to ketenes [17], or the desymmetrisation of meso-anhydrides [18]. Cinchona alkaloids present at least four points of attachment to a solid-phase. Very often the vinyl group serves to graft the alkaloids with the presence of a spacer group between the polymer backbone and the alkaloid moiety (*C*-11 bound catalysts, Figure 2). Quite often the polymer is attached at the *O*-9 hydroxy group through an ether or an ester linkage (*O*-9 bound catalysts, Figure 2). There are very few reports on the attachment

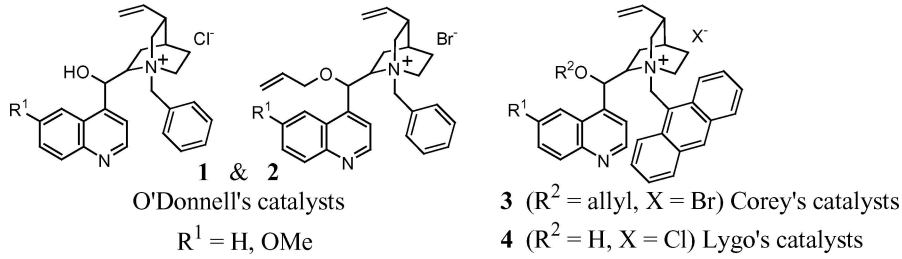


Figure 1. Three generation of cinchona-derived phase-transfer catalysts.

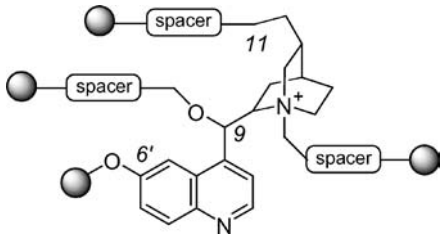
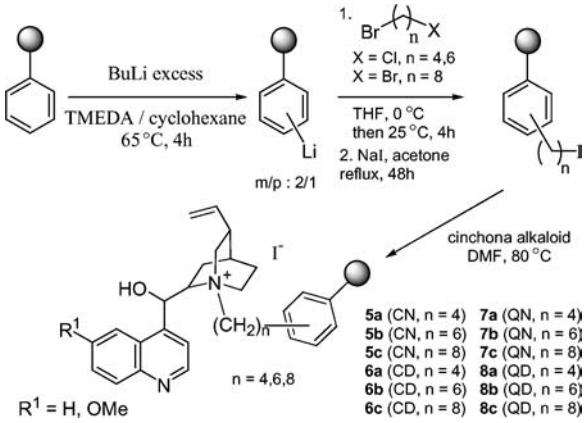


Figure 2. Points of attachment of cinchona alkaloids to a solid-phase.



Scheme 1. Synthesis of polymer-bound N-connected phase-transfer catalysts.

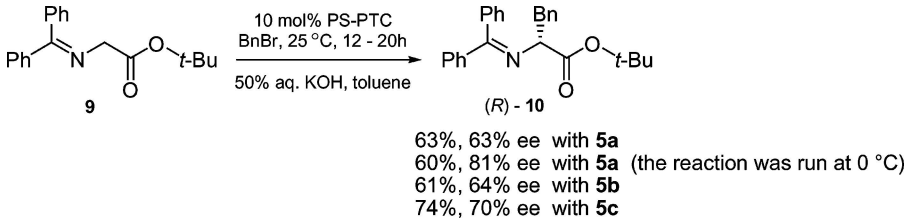
of cinchona alkaloids onto the *O*-6′ hydroxy group of cuprei(di)ne (*O*-6′-bound catalysts, Figure 2) resulting from the demethoxylation of quini(di)ne [19]. Finally, very few examples of polymeric catalysts bound to the nitrogen atom of the quinuclidine moiety were described (*N*-bound catalysts, Figure 2).

Polymer-bound N-connected phase-transfer catalysts

When we initiated the project, we reasoned that nitrogen quaternisation with a chloromethylated polystyrene should provide a convenient route to polymer-bound phase-transfer catalysts. Indeed, a Chinese group reported the enantioselective alkylation of *N*-diphenyl methylene glycine *t*-butyl ester with 27% ee using such a catalyst [20]. We decided to investigate the role of a flexible spacer between the ammonium and the polymer backbone, since we considered that distancing the alkaloid moiety from the matrix could enhance the enantioselectivity of the reaction. We exploited poly(styrene-co-divinylbenzene) (200–400 mesh, 1% cross-linked) as the solid-support. The lithiation of the polymer was performed with the aid of the complex butyllithium/TMEDA, which gave a 2/1 mixture of *m*-/*p*-regioisomers [21]. The lithiated polymer was then reacted with a bromochloro- or a dibromoalkane to introduce the spacer. Three spacer lengths were introduced: four, six and eight carbon atoms. Then, a Finkelstein halogen exchange reaction was necessary, for reasons of reactivity, to allow an easier substitution by the alkaloid. The four cinchona alkaloids, cinchonine (CN), cinchonidine (CD), quinine (QN), and quinidine (QD) were attached through the three-spacer lengths, giving twelve new chiral polymers (Scheme 1).

These polystyrene-bound phase-transfer catalysts (PS-PTC) were evaluated in the liquid/liquid/solid phase-transfer enantioselective alkylation of the *N*-diphenyl methylene glycine *t*-butyl ester **9** (Scheme 2).

We found that the enantioselectivity was strongly dependent on the alkaloid and moderately altered by the length of the spacer. Among the four cinchona alkaloids, cinchonine was selected for further investigations, and preferred



Scheme 2. Enantioselective alkylation of N-diphenyl methylene glycine *t*-butyl ester.

to cinchonidine [(*R*)-**10**, 6–29% ee], whereas the pair of diastereomers QN/QD was discarded because of the poor enantioselectivities obtained [(*R*)-**10**, 4–10% ee]. Optimisation of the reaction conditions led to an enantiomeric excess of 81% when the reaction was run at 0 °C. Unexpectedly, the same predominant enantiomer was obtained irrespective of the catalyst used, although CN and CD (or QN and QD) normally give rise to opposite enantiomers. Those alkaloids, which are diastereomers, are often termed pseudoenantiomers [22], however, in our case, the pseudoenantiomeric effect was not observed [23]. This may imply that the *O*-9 hydroxy group of the catalyst is not involved to any significant extent in the enantiotopic differentiation. By inference, the other stereogenic centres, which belong to the quinuclidine moiety and remain invariant through the four alkaloids, must be responsible for the asymmetric induction. Also, the "superstructure" of the polymers with configurational specified domains is likely to have an extra effect on the enantioselectivity of the process.

The alkylation with other electrophiles, reactive alkylating agents (allyl bromide and 2-bromomethylnaphthalene) and a simple alkyl halide (ethyl iodide), was found to be moderately enantioselective, yet not optimised (Figure 3).

We have demonstrated that this first type of PS-PTC gave good enantioselectivities (up to 81%) [24], and our results favorably compared with the supported catalysts previously reported (27% ee without spacer) [20]. During the course of our study, Nájera and co-workers reported the benzylation of *N*-diphenyl methylene glycine *t*-butyl ester using PS-PTC *N*-connected without spacer giving 58% ee [25a]. They also employed the *i*-propyl ester derivative of the Schiff base and obtained, in this case, an enantiomeric excess of 90% [25]. Our results show the importance of the spacer, between the alkaloid and the polystyrene matrix, in the model reaction using *N*-diphenyl methylene glycine *t*-butyl ester (81% vs. 58% ee). However in the reaction using *N*-diphenyl methylene glycine *i*-propyl ester, our best catalyst was less efficient than the one described by Nájera (46% vs. 90% ee), indicating a substrate-dependent enantioselective reaction.

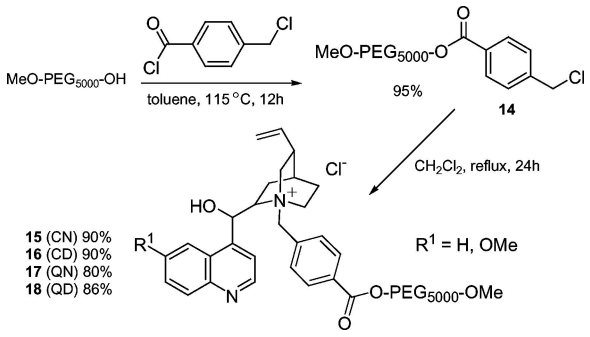
Recycling of the polymer-bound catalyst **5a** was attempted. Desperately, the recycling gave longer reaction times, lower enantiomeric excesses, and yet identical yields.

The solid-phase catalyst could possibly be improved further by changing the nature of the support to a poly(ethylene glycol) (PEG) non-cross linked matrix type. PEGs are inexpensive, available in different molecular weights, linear polymers having high solubilising properties in a wide range of solvents, and they can be easily recovered by precipitation in another appropriate solvent [26]. By using such homogeneous catalysts, we expected a higher reactivity, a higher level of enantioselectivity and an easier recycling. No mean advantage is the easy characterisation of the soluble catalysts by standard NMR techniques. PEG-supported achiral ammonium salts as phase-transfer catalysts were described by Benaglia and co-workers [27], as well as two cinchonidinium salts connected to PEG through *O*-9 and *O*-6′ applied to the benzylation of *N*-diphenyl methylene glycine *t*-butyl ester (ee up to 64%) and to the conjugate addition of thiophenol to cyclohexenone (ee 22%) [28].

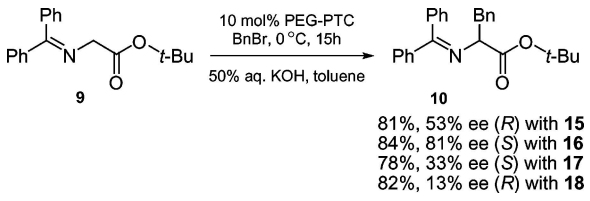
During the same period of time, we independently synthesised PEG-bound *N*-connected cinchona alkaloids possessing an aromatic spacer for the connection. On poly(ethylene glycol) monomethyl ether [MeO-PEG-OH (Mw 5000)] was reacted 4-chloromethylbenzoyl chloride in refluxing toluene. The resulting polymer **14** having a terminal chloromethyl group was refluxed in dichloromethane with each of the four cinchona alkaloids to afford four new PEG-bound catalysts **15–18** by quaternisation of the bridgehead nitrogen (Scheme 3).

The catalytic asymmetric behavior of these PEG-bound catalysts was examined in the liquid/liquid phase-transfer benzylation of **9** (Scheme 4) [29].

Screening of the four polymers showed that diastereomeric catalysts **15** and **16** were superior to the diastereomeric pair **17/18**. Noteworthy, CD-derived PEG-PTC **16** gave higher enantioselectivity than CN derivative **15**, whereas it was the opposite with PS-PTC (**5** and **6**). With PEG-PTC, the pseudoenantiomeric effect was observed with **15** giving



Scheme 3. Synthesis MeO-PEG$_{5000}$ *N*-bound cinchona alkaloids.



Scheme 4. Enantioselective benzylation of **9** using MeO-PEG$_{5000}$ *N*-bound cinchona alkaloids.

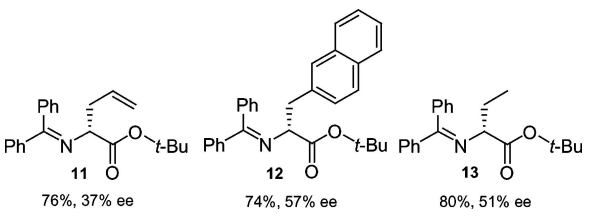


Figure 3. Alkylation with other electrophiles.

the (*R*) enantiomer and **16** the (*S*) enantiomer. In addition, the reaction times were significantly shorter than with heterogeneous PS-PTC catalysts; the reactions were completed within 15 h.

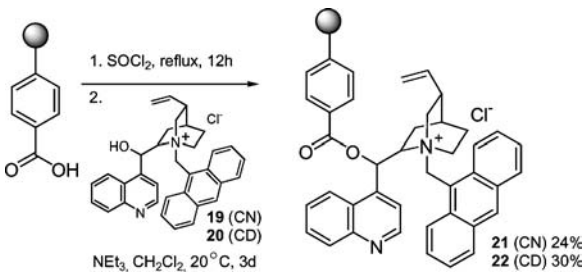
Next, we studied the influence of the PEG chain length using a PEG with an average molecular weight of 750. The synthetic pathway shown in Scheme 3 was employed to prepare four PEG_{750}-PTC, bearing each of the four cinchona alkaloids, and they were evaluated in the benzylation of **9**. None of the four PEG_{750}-PTCs gave satisfactory enantioselectivity [ee's ranging from 3% (for QN) to 25% ee (for CD)], although the catalytic activity was preserved (similar yields and reaction times).

All these observations clearly demonstrated that the PEG support behaved differently compared to the polystyrene matrix. The PEG support was further developed in the design of other supported-catalysts (later in the text).

Polymer-bound (O-9)-connected phase-transfer catalysts

The bridgehead nitrogen, which bears a methylene or a benzyl spacer in the polymer-bound *N*-connected phase-transfer catalysts **5–8** and **15–18**, is not as sterically hindered in comparison to unsupported catalysts **3** and **4** having a methylanthracenyl group. Thus, we have developed another type of polymer, exploiting the *O*-9 hydroxy group of the alkaloids to connect the polystyrene matrix, through an ester or an ether linkage, and leaving free the nitrogen atom of the quinuclidine moiety for quaternisation with the aid of 9-chloromethylanthracene.

In a first series of experiments, cross-linked polystyrene-bound cinchona alkaloid salts were obtained by heterogenisation of *N*-(9-anthracenylmethyl) cinchona idinium chloride by means of the commercially available cross-linked carboxypolystyrene resin [1% divinylbenzene (DVB)]. The sequence quaternisation/grafting on the polymer was preferred to the reverse one for reasons of efficiency. The carboxylic acid function reacted in thionyl chloride at reflux to give the acyl chloride, then, after removal of the excess of thionyl chloride under vacuum, a solution of *N*-(9-anthracenylmethyl) cinchona idinium chloride in dichloromethane was added to the polymer, and the mixture was stirred for three days at room temperature (Scheme 5). Two cinchona idinium salts



Scheme 5. Grafting of cinchoninium and cinchonidinium salts on a carboxypolystyrene resin.

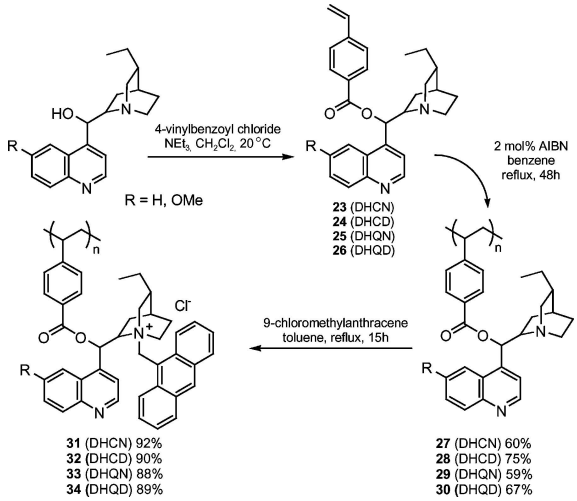
Table 1. Evaluation of catalysts **21**, **22** and **31–34** in the benzylation of **9**[a]

Entry	Catalyst	Time (h)	Yield (%)[b]	ee (%)[c]
1	**21** (CN)	96	62	65 (*R*)
2	**22** (CD)	120	57	30 (*S*)
3	**31** (DHCN)	16	65	34 (*R*)
4	**32** (DHCD)	16	82	85 (*S*)
5	**33** (DHQN)	24	71	43 (*S*)
6	**34** (DHQD)	15	81	67 (*R*)

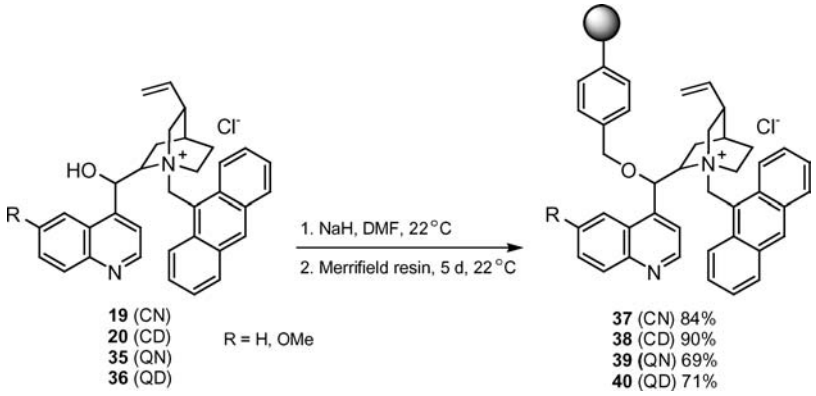
[a]The reactions were run in toluene and 50% aqueous potassium hydroxide at 0 °C with 10 mol% catalyst.
[b]Isolated yields.
[c]Determined by HPLC analysis using Chiralcel OD-H. The absolute configuration was determined by comparison of optical rotation with literature report in Ref. [3].

were grafted, **19** (CN) and **20** (CD), which best performed in the previous studies. Yields and loading values were determined by nitrogen analysis (0.24 mmol g^{-1} for **21** and 0.30 mmol g^{-1} for **22**). Although the overall yields for the synthesis of **21** and **22** are low, they were evaluated in the benzylation of the glycine Schiff base **9** (Table 1).

Soluble polystyrenic supports have not received as much attention as their cross-linked, insoluble counterparts. However, linear polymers are soluble in a wide range of solvents and are easily recovered by precipitation in another appropriate solvent for recycling. Soluble polymeric cinchona alkaloid-based phase-transfer catalysts were obtained by polymerisation of the dihydro cinchona alkaloid *O*-9-(4-vinylbenzoate) **23–26** in the presence of a catalytic amount of AIBN in refluxing dry benzene. This synthetic approach allowed getting high loadings of catalysts unlike the use of Merrifield resins. The resulting homopolymers **27–30** were reacted with 9-chloromethylanthracene for quaternisation of the nitrogen atom of the quinuclidine moiety, leading to catalysts **31–34** in high yields (88–92%, determined by weighing) (Scheme 6).



Scheme 6. Preparation of poly[*O*-9-(4-vinylbenzoyl)-*N*-methylanthracenyl dihydro cinchona idinium chloride] **31–34**.



Scheme 7. Preparation of *O*-9-(4-methylpolystyrenyl)-*N*-9-methylanthracenyl cinchona idinium chloride.

The insoluble polystyrene-bound catalysts **21** and **22** required long reaction times, and gave moderate enantioselectivities in the benzylation of **9** (entries 1 and 2, Table 1). Interestingly, the soluble analogues were more efficient, with reactions completed within 24 h, and more enantioselective, allowing ee's up to 85% in the case of catalyst **32** (entries 3–6, Table 1).

Attempt to reuse catalyst **32** failed to give good conversion, clearly indicating a degradation of the structure, perhaps the cleavage of the ester linkage. For this reason, we considered a synthetic plan to polymer-bound (*O*-9)-connected phase-transfer catalysts via a more robust ether linkage. The four cinchona alkaloids were quaternarised with the aid of 9-chloromethylanthracene and grafted to a Merrifield resin (1.7 mmol $Cl \cdot g^{-1}$, 1% DVB, 200–400 mesh) after treatment of the alkaloid salts by sodium hydride in DMF (Scheme 7) [30].

These new catalysts were tested in the model reaction. At 0 °C the cinchonidine-based catalyst **38** gave 79% ee, with the pseudoenantiomeric effect observed when switching to the cinchonine-based catalyst **37**, although with lower ee (entries 1–2, Table 2). In this series of polystyrene-bound catalysts, we were able to work at lower temperature under liquid/solid/solid conditions with solid cesium hydroxide monohydrate. At −40 °C, the enantioselectivities were substantially higher so that using catalyst **38** the benzylation produced **10** in 93% ee. The enantioselectivity was further improved to 94% ee in 67% yield at −50 °C while it failed to react at −78 °C (entries 6, 9 and 10, Table 2). This result compared with the solution-phase approach, reported by Corey, which gave 94% ee for the benzylation of **9** [3].

To further continue in this investigation, we sought to synthesise (*O*-9)-connected catalysts bearing a spacer between the alkaloid and the polystyrene matrix. For this purpose, we used the 4-iodobutyl polystyrene instead of the Merrifield resin in the reaction shown in Scheme 7, to yield catalyst **41** (Figure 4). However, **41** provided an enantiomeric excess of 81% only, under the reaction conditions that gave 94% ee with catalyst **38** not possessing a spacer.

At this point, we decided to study the recycling of our most successful catalyst **38**. Upon completion of the benzylation of **9**, filtration and several washings of the polymer allowed recovering the catalyst for reuse; results of the recycling are summarised in Table 3. Reaction times considerably increased from the third cycle, and the enantiomeric excess dropped to 74%. Obviously, the catalyst suffered from chemical and physical damages. In order to limit some damages, we synthesised a more robust, more reticulated, polymer cross-linked with 1.5% DVB. The recycling of **38** (1.5% DVB) appeared more efficient yet not completely satisfactory (Table 3, right part). We observed an extension of reaction times, although not as large as in the case of **38** (1% DVB),

Table 2. Evaluation of catalysts **37–40** in the benzylation of **9**

Entry	Catalyst	Base	T (°C)	Time (h)[a]	Yield (%)[b]	ee (%)[c]
1	**37** (CN)	50% aq KOH	0	72	58	59 (*R*)
2	**38** (CD)	50% aq KOH	0	48	63	79 (*S*)
3	**39** (QN)	50% aq KOH	0	72	53	26 (*S*)
4	**40** (QD)	50% aq KOH	0	72	51	16 (*R*)
5	**37** (CN)	$CsOH.H_2O$	−40	48	48	23 (*R*)
6	**38** (CD)	$CsOH.H_2O$	−40	27	64	93 (*S*)
7	**39** (QN)	$CsOH.H_2O$	−40	48	49	36 (*S*)
8	**40** (QD)	$CsOH.H_2O$	−40	48	46	26 (*R*)
9	**38** (CD)	$CsOH.H_2O$	−50	30	67	94 (*S*)
10	**38** (CD)	$CsOH.H_2O$	−78	48	0	–

[a]The reaction was quenched when no further conversion was observed by TLC.
[b,c]See Table 1.

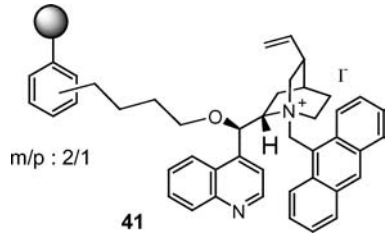


Figure 4. Cinchonidinium salt linked to polystyrene through a 4-carbon spacer.

Table 3. Recycling of catalyst **38** in the benzylation of **9**

Catalyst **38** (1% DVB)[a]				Catalyst **38** (1.5% DVB)[a]			
Run	Reaction time (h)	Yield (%)	ee (%)	Run	Reaction time (h)	Yield (%)	ee (%)
1	27	64	93	1	20	84	95
2	33	59	87	2	28	75	96
3	48	46	77	3	34	69	92
4	96	48	74	4	45	70	88

[a]The reactions were run in toluene at −40 °C with 10 mol% **38** and $CsOH \cdot H_2O$ as the base.

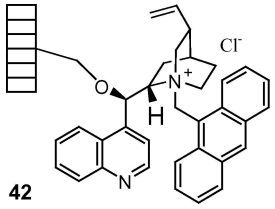


Figure 5. Catalyst supported on a SynPhase^{TM} lantern.

and a moderate lowering of the enantiomeric excesses (95 to 88% ee).

In order to minimise physical deterioration of the catalyst, due to magnetic stirring, we performed the synthesis on SynPhase^{TM} lanterns, which are constituted of chloromethylated polystyrene stacked disks [31]. Grafting of *N*-9-methylanthracenyl cinchonidinium chloride to the chloromethylated lantern was carried out by treatment of the alkaloid with sodium hydride in DMF to yield the catalyst on lantern **42** (Figure 5), which was suspended in the reaction vessel for the benzylation of **9**. Interestingly, three successive uses of **42** gave constant reaction time (24 h), yield (68–72%) and enantioselectivity (77–78%). The lantern allowed stability of the results, implying a negligible physical deterioration of the catalyst, although with slightly lower enantioselectivities.

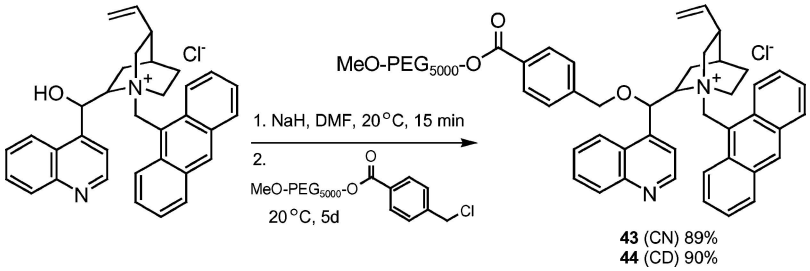
Table 4. Evaluation of PEG-bound catalysts **43–46** in the benzylation of **9**

Entry	Catalyst	Base	T (°C)	Time (h)[a]	Yield (%)[b]	ee (%)[c]
1	**43** (CN)	50% aq KOH	0	19	86	14 (*R*)
2	**44** (CD)	50% aq KOH	0	15	74	54 (*S*)
3	**45** (CN)	50% aq KOH	0	15	85	29 (*R*)
4	**46** (CD)	50% aq KOH	0	15	83	62 (*S*)
5	**46** (CD)	$CsOH.H_2O$	−60	72	67	71 (*S*)

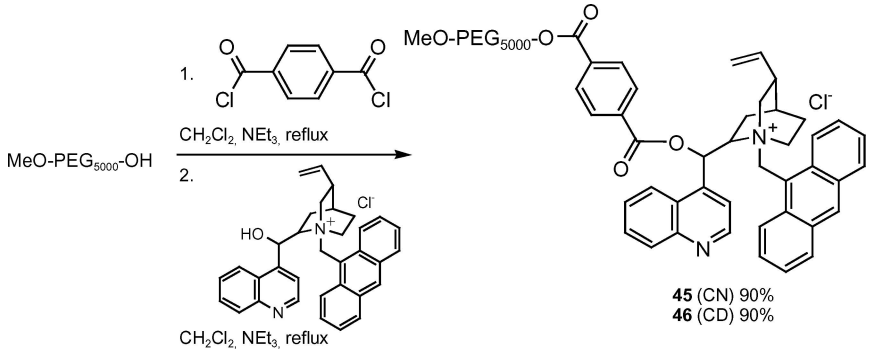
[a,b,c]See Table 2.

Exploring *O*-9 hydroxy group as the attachment site, we also considered PEGs to get soluble catalysts. Two possible linkages between the hydroxy group and the alkaloid were considered: ether and ester linkage. The preparation of the catalysts is described in Schemes 8 and 9, and the results of their evaluation in the benzylation of **9** is reported in Table 4.

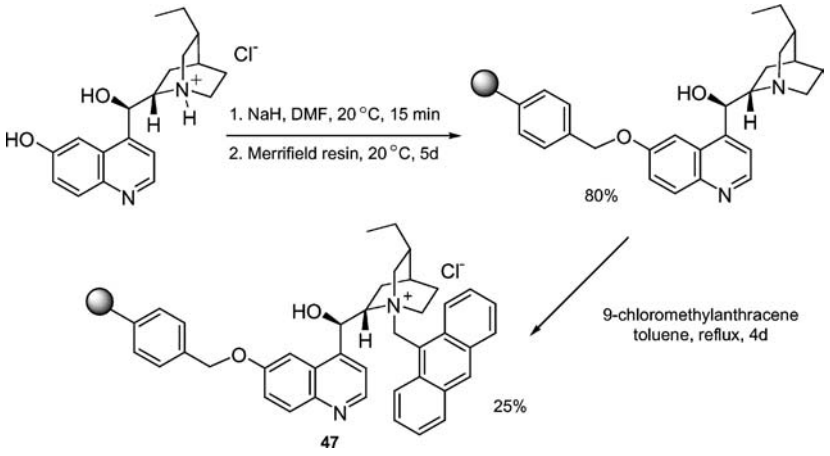
A maximum ee of 62% was recorded under the best conditions found for the use of catalysts **15** and **16**. This was unexpected considering the higher efficiency of *N*-methylanthracenyl cinchona idinium salts. All the same, the enantioselectivity was slightly improved when the reaction was run at −60 °C with solid cesium hydroxide monohydrate (entry 5, Table 4).



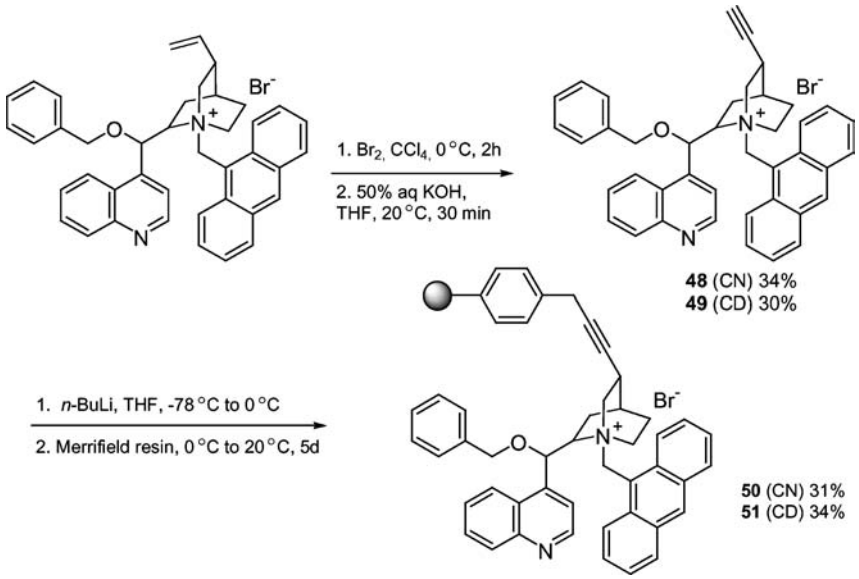
Scheme 8. Synthesis of MeO-PEG_{5000}-*O*-9-bound catalysts (ether linkage).



Scheme 9. Synthesis of MeO-PEG_{5000}-*O*-9-bound catalysts (ester linkage).



Scheme 10. Synthesis of (*O*-6′)-connected phase-transfer catalyst **47**.



Scheme 11. Synthesis of (*C*-11)-connected phase-transfer catalysts **50** and **51**.

Polymer-bound (O-6′)-connected phase-transfer catalysts

Demethoxylation of dihydroquini(di)ne provides an interesting aromatic hydroxy group for connection to polymers. There are very few examples of demethoxylated quinine or quinidine derivatives grafted on polymeric supports [28, 32]. The demethoxylation of dihydroquinine was carried out following Heidelberger's method in refluxing concentrated HBr to give the dihydrocupreine [19]. Then, the dihydrocupreine (via its hydrochloride salt) was anchored on a Merrifield resin followed by quaternisation of the nitrogen atom of the quinuclidine moiety to give catalyst **47** in 25% yield (Scheme 10).

In the benzylation reaction of glycine Schiff base **9**, catalyst **47** gave the benzylated amino acid derivative, but failed to promote enantioselectivity higher than 2%.

Polymer-bound (C-11)-connected phase-transfer catalysts

Finally, we anchored the alkaloids (CN and CD) through the vinyl group of the alkaloids, thus preserving the organocatalytic amino alcohol moiety. The vinyl group was transformed into a terminal alkyne (**48** and **49**) [33], which was

Table 5. Evaluation of (*C*-11)-connected phase-transfer catalysts **50** and **51**

Entry	Catalyst	Base	T (°C)	Time (h)[a]	Yield (%)[b]	ee (%)[c]
1	**50** (CN)	50% aq KOH	20	20	70	63(*R*)
2	**51** (CD)	50% aq KOH	20	18	94	11 (*S*)
3	**50** (CN)	50% aq KOH	0	26	72	73 (*R*)
4	**50** (CN)	$CsOH.H_2O$	−40	30	69	71 (*R*)

[a,b,c] See Table 2.

further deprotonated to react with a Merrifield resin affording the catalysts **50** and **51** (Scheme 11).

These catalysts promoted the benzylation of **9** with moderate enantioselectivities (Table 5).

Conclusion

A collection of 35 new polymer-bound phase-transfer catalysts were synthesised and evaluated in the alkylation of *N*-diphenyl methylene glycine *t*-butyl ester. This work provides an interesting insight into how best to attach the alkaloid to the polymer backbone. The polystyrene (1.5% DVB)-bound *O*-9-connected phase-transfer catalysts exhibited high enantioselectivities (up to 96% ee), which were superior to those obtained in the solution-phase approach. The main conclusions, which can be drawn from this study, are summarised as follows: (i) In terms of enantioselectivity, both *N*- and *O*-9-connected catalysts appear much more powerful than their *O*-6′- and *C*-11-connected congeners. Providing optimisation of polymeric support, spacer chain length and chemical nature of the link, high ee's are attained. (ii) In terms of recyclability, two successful and promising approaches are described when using *O*-9 ether link as connection onto either a reticulated polymer or a lantern.

Experimental section

General

^{1}H and ^{13}C NMR spectra were recorded on a Bruker DPX 300 spectrometer in $CDCl_3$, and δ (ppm) is quoted relative to the residual signal of $CDCl_3$ (^{1}H NMR $\delta_H = 7.27$ ppm; ^{13}C NMR $\delta_C = 77.2$ ppm). HPLC was carried out using a Waters 600 apparatus equipped with Chiralcel columns. Specific rotations were measured with a Perkin-Elmer M341 polarimeter. IR spectra were recorded on a Perkin-Elmer 16 PC FT-IR. Flash chromatography was performed on silica gel Merck Kieselgel 60 (230–400 Mesh). THF was dried by heating under reflux over Na and benzophenone followed by distillation. CH_2Cl_2, benzene, and toluene were freshly distilled from CaH_2 under N_2.

Synthesis of polymer-bound *N*-connected phase-transfer catalysts

Polystyrene-bound PTCs **5–8**

To a solution of poly(styrene-*co*-divinylbenzene) (1% cross-linked, 200–400 mesh) (5 g, 48 mmol) in cyclohexane (50 mL) under argon atmosphere were added TMEDA (7.24 mL, 48 mmol) and n-butyllithium (24 mL, 2.5 M in hexane). The mixture was stirred for 4 h at 65 °C. The liquid phase was then removed, replaced by cyclohexane (30 mL) and the procedure for lithiation was repeated a second time. The lithiated polymer was then washed four times with dry THF. Then, THF (30 mL) was added to the polymer (2 mmol of lithium $\cdot\, g^{-1}$, 10 mmol) and the mixture was cooled to 0 °C. The dihalogenoalkane (see Scheme 1) (20 mmol) was introduced in THF (10 mL) and the mixture was stirred at room temperature for 4 h. The reaction was quenched by water (10 mL), and the polymer was washed with THF (20 mL), ethanol (20 mL) and the halogenoalkyl polystyrene was dried in vacuo (20 mmHg).

To a solution of the halogenoalkyl polystyrene (1 g, 2 mmol) in acetone (20 mL) was introduced sodium iodide (2.9 g, 20 mmol). The mixture was then refluxed for 48 h. After cooling, the polymer was obtained by filtration and washed several times with methanol, THF, water, acetone, dichloromethane. The iodoalkyl polystyrene was then dried in vacuo (20 mmHg).

To a solution of iodoalkyl polystyrene (1 g, 2 mmol $I \cdot g^{-1}$) in DMF (30 mL) was added the alkaloid (4 mmol). The mixture was then heated at 80 °C for 24 h. The polymer was obtained by filtration and washed several times with methanol, THF, water, acetone, dichloromethane. The polymer-bound *N*-connected phase-transfer catalyst was then dried in vacuo (20 mmHg).

4-N-cinchoninium butylpolystyrene iodide **5a**. Yield: 75%; IR (KBr): 2923, 1946, 1870, 1807, 1601, 1453, 1343, 762, 700 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 4.18; loading = 1.5 mmol g^{-1}.

6-N-cinchoninium hexylpolystyrene iodide **5b**. Yield: 49%; IR (KBr): 3024, 2929, 1940, 1866, 1806, 1602, 1454, 762, 701 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 2.60; loading = 0.9 mmol g^{-1}.

8-N-cinchoninium octylpolystyrene iodide **5c**. Yield: 43%; IR (KBr): 2954, 1939, 1896, 1710, 1616, 1260, 1020, 830, 702 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 2.44; loading = 0.9 mmol g^{-1}.

4-N-cinchonidinium butylpolystyrene iodide **6a**. Yield: 45%; IR (KBr): 3030, 2946, 2845, 1949, 1894, 1811, 1746, 1603, 1498, 1465, 761, 715 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 2.53; loading = 0.9 mmol g^{-1}.

6-N-cinchonidinium hexylpolystyrene iodide **6b**. Yield: 43%; IR (KBr): 3031, 2926, 1962, 1890, 1818, 1607, 1506, 1468, 768 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 2.45; loading = 0.9 mmol g^{-1}.

8-N-cinchonidinium octylpolystyrene iodide **6c**. Yield: 49%; IR (KBr): 3029, 2936, 1954, 1893, 1794, 1627, 1497, 768 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 2.78; loading = 1.0 mmol g^{-1}.

4-N-quininium butylpolystyrene iodide **7a**. Yield: 56%; IR (KBr): 2916, 1940, 1875, 1807, 1601, 1454, 1029, 760, 699 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 3.16; loading = 1.1 mmol g^{-1}.

6-N-quininium hexylpolystyrene iodide **7b**. Yield: 44%; IR (KBr): 2926, 2853, 1945, 1872, 1805, 1621, 1454, 1359, 1239, 701 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 2.48; loading = 0.9 mmol g^{-1}.

8-N-quininium octylpolystyrene iodide **7c**. Yield: 37%; IR (KBr): 2943, 1946, 1873, 1803, 1608, 1454, 1348, 760, 700 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 2.11; loading = 0.8 mmol g^{-1}.

4-N-quinidinium butylpolystyrene iodide **8a**. Yield: 53%; IR (KBr): 2928, 1940, 1873, 1805, 1601, 1455, 1029, 702 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 2.96; loading = 1.1 mmol g^{-1}.

6-N-quinidinium hexylpolystyrene iodide **8b**. Yield: 53%; IR (KBr): 2938, 1940, 1866, 1731, 1614, 1504, 1239, 1028, 827, 702 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 2.98; loading = 1.1 mmol g^{-1}.

8-N-quinidinium octylpolystyrene iodide **8c**. Yield: 36%; IR (KBr): 3029, 2933, 2849, 1944, 1899, 1812, 1748, 1504, 761, 715 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 2.06; loading = 0.7 mmol g^{-1}.

PEG-bound PTCs **15–18**

Synthesis of MeO-PEG_{5000}-*p*$ClCH_2$Bz **14**: To a solution of poly(ethylene glycol) monomethyl ether (Mw 5000) (11.02 g, 2.20 mmol) in toluene (200 mL) was added 4-chloromethylbenzoyl chloride (500 mg, 2.64 mmol) and the mixture was refluxed for 12 h. The solution was then cooled to room temperature, concentrated to about 10 mL and poured onto diethyl ether (250 mL). The polymer was filtered, washed several times with diethyl ether and dried under vacuum at 50 °C for 12 h. Yield: 95%; IR ($CHCl_3$): 2889, 2741, 1965, 1715, 1469, 1279, 1113, 842 cm^{-1}; ^{1}H NMR: δ 8.06 (d, 2H, J = 8.4 Hz), 7.48 (d, 2H, J = 8.4 Hz), 4.63 (s, 2H), 4.49 (m, PEG), 3.65 (m, PEG).

To a solution of **14** (1 g, 0.19 mmol) in dichloromethane (30 mL) was added the alkaloid (0.20 mmol) and the mixture was refluxed for 24 h. The solution was then cooled to room temperature, concentrated to about 5 mL and poured onto diethyl ether (100 mL). The polymer was collected by filtration, and dried under vacuum at 50 °C to afford the PEG-bound catalysts.

MeO-PEG_{5000} N-bound cinchoninium chloride **15**. Yield: 90%; $[\alpha]_D^{25}$ = +13.3 (c = 0.3, $CHCl_3$); ^{1}H NMR: δ 8.84 (d, 1H, J = 4 Hz), 8.06 (m, 4H), 7.55 (m, 2H), 7.39 (M, 3H), 5.65 (m, 1H), 5.23 (m, 1H), 4.96 (m, 3H), 4.55 (s, 2H), 4.41 (m, 2H, PEG), 3.58 (m, PEG), 2.84 (m, 2H), 2.54 (m, 3H), 2.17 (m, 1H), 1.74 (m, 3H), 1.49 (m, 2H); loading = 0.18 mmol g^{-1}.

MeO-PEG_{5000} N-bound cinchonidinium chloride **16**. Yield: 90%; $[\alpha]_D^{25}$ = −4.3 (c = 0.3, $CHCl_3$);^{1}H NMR: δ 8.83 (d, 1H, J = 4 Hz), 8.00 (m, 4H), 7.54 (m, 2H), 7.39 (m, 3H), 5.64 (m, 1H), 5.17 (m, 1H), 4.88 (m, 1H), 4.62 (s, 2H), 4.50 (m, 2H, PEG), 3.65 (m, PEG), 3.10 (m, 2H), 2.67 (m, 3H), 2.27 (m, 1H), 1.75 (m, 3H), 1.48 (m, 2H); loading = 0.18 mmol g^{-1}.

MeO-PEG_{5000} N-bound quininium chloride **17**. Yield: 80%; $[\alpha]_D^{25}$ = −3.7 (c = 0.3, $CHCl_3$);^{1}H NMR: δ 8.69 (d, 1H, J = 4 Hz), 7.97 (m, 3H), 7.51 (m, 2H), 7.34 (m, 2H), 7.27 (m, 1H), 5.92 (m, 1H), 5.22 (m, 1H), 5.02 (m, 1H), 4.60 (s, 2H), 4.41 (m, 2H, PEG), 3.64 (PEG), 3.08 (m, 2H), 2.91 (m, 1H), 2.80 (m, 1H), 2.57 (m, 1H), 2.24 (m, 1H), 1.96 (m, 4H), 1.75 (m, 2H), 1.52 (m, 2H), 1.16 (m, 1H); loading = 0.16 mmol g^{-1}.

MeO-PEG_{5000} N-bound quinidinium chloride **18**. Yield: 86%; $[\alpha]_D^{25}$ = +15.7 (c = 0.3, $CHCl_3$);^{1}H NMR: δ 8.68 (d, 1H, J = 4 Hz), 7.97 (m, 3H), 7.53 (m, 2H), 7.38 (m, 2H), 7.31 (m, 1H), 5.95 (m, 1H), 5.21 (m, 1H), 5.02 (m, 1H), 4.56 (s, 2H), 4.39 (m, 2H, PEG), 3.62 (m, PEG), 3.11 (m, 1H), 2.89 (m, 2H), 2.80 (m, 1H), 2.56 (m, 1H), 2.23 (m, 1H), 1.95 (m, 4H), 1.74 (m, 2H), 1.53 (m, 2H), 1.18 (m, 1H); loading = 0.17 mmol g^{-1}.

Polymer-bound (O-9)-connected phase-transfer catalysts

O-9-(4-carboxypolystyrenyl)-N-9-methylanthracenyl cinchona idinium chloride **21–22**

A solution of carboxypolystyrene (1% crossedlinked with DVB, 0.8–1.2 mmol g^{-1}) (200 mg, 0.2 mmol) in thionyl chloride (10 mL) was refluxed for 12 h. The mixture was then cooled to room temperature and the thionyl chloride in excess was removed in vacuo. To the polymer was then introduced at 0 °C dichloromethane (10 mL), the *N*-9-methylanthracenyl cinchona idinium chloride **19** or **20** (0.3 mmol) and triethylamine (30 μL, 0.2 mmol). The mixture was then stirred at room temperature for 5 days. The polymer was obtained by filtration and washed several times with methanol, THF, water, acetone, dichloromethane and methanol and dried in vacuo (20 mmHg).

O-9-(4-carboxypolystyrenyl)-N-9-methylanthracenyl cinchoninium chloride **21**. Yield: 24%; IR (KBr): 3062, 2928, 1942, 1888, 1800, 1738, 1600, 1487, 1071, 752 cm^{-1}; Anal. Calcd for f_{max}: N, 2.80 Found: N, 0.67; loading = 0.25 mmol g^{-1}.

O-9-(4-carboxypolystyrenyl)-N-9-methylanthracenyl cinchonidinium chloride **22**. Yield: 30%; IR (KBr): 3024, 2936, 1953, 1769, 1604, 1173, 881 cm^{-1}; Anal. Calcd for f_{max}: N, 2.80 Found: N, 0.84; loading = 0.30 mmol g^{-1}.

Poly(4-vinylbenzoyl N-9-methylanthracenyl dihydrocinchona idinium chloride) **31–34**

Synthesis of 4-vinyl- benzoyl dihydrocinchona alkaloid
A solution of 4-vinylbenzoic acid (500 mg, 3.38 mmol) in thionyl chloride (4.92 mL, 67.6 mmol) was refluxed for 1 h. After cooling the mixture to room temperature, the excess of thionyl chloride was removed by concentration of the mixture under reduced pressure to afford 4-vinylbenzoyl chloride (562.5 mg, 3.38 mmol). To this brown solid was then added under nitrogen at room temperature freshly distilled dichloromethane (20 mL), the dihydro alkaloid (3.38 mmol) and triethylamine (470 μL, 3.38 mmol). The mixture was stirred for 15 h at room temperature. The reaction was then quenched with water, and the organic layer was washed with 1M sodium carbonate solution, brine, dried and concentred under reduced pressure. The solid was then purified by flash chromatography (acetone/ethyl acetate:4/1) to afford a white solid (**23–26**).

4-vinylbenzoyl dihydrocinchonine **23**. Yield: 73%;^{1}H NMR: δ 8.78 (d, 1H, J = 4.5 Hz), 8.23 (d, 1H, J = 9 Hz), 8.00 (m, 2H), 7.60 (m, 2H), 7.40 (m, 4H), 6.69 (d, 1H, J = 7 Hz), 6.61 (m, 1H), 5.88 (d, 1H, J = 18 Hz), 5.33 (d, 1H, J = 12 Hz), 3.36 (d, 1H, J = 9 Hz), 2.81–2.53 (m, 3H), 1.77 (m, 1H), 1.40 (m, 6H), 1.24 (m, 2H), 0.77 (t, 3H, J = 7 Hz); ^{13}C NMR: δ 165.8, 1504, 149.0, 146.1, 142.8, 136.3, 130.9, 130.4, 129.9, 129.2, 127.2, 126.7, 126.5, 123.9, 119.1, 117.3, 74.8, 60.4, 51.1, 50.4, 37.8, 27.6, 26.5, 25.8, 24.2, 12.4.

4-vinylbenzoyl dihydrocinchonidine **24**. Yield: 75%;^{1}H NMR: δ 8.78 (d, 1H, J = 4.5 Hz), 8.16 (d, 1H, J = 9 Hz), 7.97 (m, 2H), 7.76 (m, 2H), 7.44 (m, 4H), 6.76 (d, 1H, J = 7 Hz), 6.73 (m, 1H), 5.80 (d, 1H, J = 18 Hz), 5.33 (d, 1H, J = 12 Hz), 3.39 (d, 1H, J = 9 Hz), 2.79–2.55 (m, 3H), 1.75 (m, 1H), 1.39 (m, 6H), 1.20 (m, 2H), 0.77 (t, 3H, J = 7 Hz); ^{13}C NMR: δ 165.4, 150.4, 148.9, 142.9, 136.2, 130.9, 130.6, 130.4, 129.7, 129.2, 128.2, 127.5, 126.8, 126.2, 123.8, 117.4, 75.0, 60.0, 58.8, 54.2, 37.7, 28.8, 28.0, 25.7, 24.0, 12.5.

4-vinylbenzoyl dihydroquinine **25**. Yield: 59%;^{1}H NMR: δ 8.59 (d, 1H, J = 4.5 Hz), 7.90 (m, 3H), 7.40 (s, 1H), 7.23 (m, 2H), 7.20 (d, 2H, J = 2 Hz), 6.65 (d, 1H, J = 7 Hz), 6.53 (m, 1H), 5.67 (d, 1H, J = 18 Hz), 5.18 (d, 1H, J = 11 Hz), 3.81 (s, 3H), 3.27 (m, 1H), 2.77 (m, 1H), 2.62 (m, 3H), 1.85 (m, 1H), 1.77 (s, 1H), 1.48–1.18 (m, 6H), 1.07 (m, 1H), 0.73 t, 3H, J = 7 Hz); ^{13}C NMR: δ 165.7, 158.3, 147.8, 145.1, 144.4, 142.8, 136.1, 132.1, 130.3, 129.1, 127.4, 126.6, 122.3, 119.0, 117.3, 101.8, 74.5, 59.8, 55.9, 51.1, 50.3, 37.7, 27.5, 26.5, 25.8, 23.8, 12.3.

4-vinylbenzoyl dihydroquinidine **26**. Yield: 82%; ^{1}H NMR: δ 8.64 (d, 1H, J = 4.5 Hz), 7.97 (m, 3H), 7.44 (s, 1H), 7.35 (m, 2H), 7.31 (d, 2H, J = 2 Hz), 6.69 (d, 1H, J = 7 Hz), 6.63 (m, 1H), 5.78 (d, 1H, J = 18 Hz), 5.32 (d, 1H, J = 11 Hz), 3.90 (s, 3H), 3.71 (m, 1H), 3.00 (m, 1H), 2.95 (m, 3H), 2.54 (m, 1H), 2.16 (s, 1H), 1.77–1.39 (m, 6H), 1.15 (m, 1H), 0.78 (t, 3H, J = 7 Hz); ^{13}C NMR: δ 165.7, 158.4, 147.9, 145.2, 144.2, 142.9, 136.2, 132.2, 130.4, 129.2, 127.3, 126.7, 122.3, 119.0, 117.4, 101.8, 75.0, 59.7, 58.9, 56.1, 43.2, 37.8, 28.2, 25.8, 24.2, 21.5, 12.5.

Synthesis of poly(4-vinylbenzoyl dihydrocinchona alkaloid)
A solution of 4-vinylbenzoyl dihydrocinchona alkaloid (2.19 mmol) and azobisisobutyronitrile (7.0 mg, 0.04 mmol) in dry benzene (20 mL) was refluxed under nitrogen atmosphere. After 48 h, the solution was cooled to room temperature, concentrated to about 5 mL and poured onto diethyl ether. The precipitate was filtered, washed with ethanol and dried to afford the polymers **27–30**.

Poly(4-vinylbenzoyl dihydrocinchonine) **27**. Yield: 60%;^{1}H NMR: δ 8.77 (m, 1H), 7.69 (m, 2H), 7.60 (m, 2H), 7.57 (m, 1H), 7.39 (m, 4H), 2.94 (m, 1H), 2.90 (m, 2H), 1.71–1.41 (m, 13H), 0.80 (m, 3H).

Poly(4-vinylbenzoyl dihydrocinchonidine) **28**. Yield: 75%; ^{1}H NMR: δ 8.67 (m, 1H), 7.61 (m, 2H), 7.58 (m, 2H), 7.49 (m, 1H), 7.40 (m, 4H), 2.93 (m, 1H), 2.91 (m, 2H), 1.72–1.39 (m, 13H), 0.79 (m, 3H).

Poly(4-vinylbenzoyl dihydroquinine) **29**. Yield: 59%;^{1}H NMR: δ 8.57 (m, 1H), 7.77 (m, 3H), 7.31 (m, 1H), 7.13 (m, 2H), 6.59 (m, 2H), 3.76 (s, 3H), 3.17–2.88 (m, 4H), 2.48 (m, 1H), 2.16 (m, 1H), 1.52–1.01 (m, 10H), 0.58 (m, 3H); ^{13}C NMR: δ 167.0, 158.3, 147.8, 146.9, 143.2, 132.2, 128.3, 128.2, 127.1, 122.6, 122.5, 118.7, 101.7, 74.9, 59.5, 59.4, 58.6, 43.2, 37.6, 28.1, 28.0, 25.7, 12.4; $[\alpha]_D{}^{23}$ +197.2 (c 1.21, $CHCl_3$); Anal. Calcd for $C_{29}H_{32}N_2O_3$: C, 76.03; H, 7.06; N, 6.14; O, 10.51. Found: C, 76.33; H, 7.33; N, 5.87; O, 10.47.

Poly(4-vinylbenzoyl dihydroquinidine) **30**. Yield: 67%;^{1}H NMR: δ 8.64 (m, 1H), 7.96 (m, 3H), 7.43 (m, 1H), 7.36 (m, 2H), 7.31 (m, 2H), 6.68 (m, 1H,), 6.64 (m, 1H), 3.90 (s, 3H), 3.71 (m, 1H), 3.00 (m, 1H), 2.95 (m, 3H), 2.54 (m, 1H), 2.16 (m, 1H), 1.81–1.37 (m, 10H), 1.15 (m, 1H).

Synthesis of poly(4-vinylbenzoyl N-9-methylanthracenyl dihydrocinchona idinium chloride)
To a solution of poly(4-vinylbenzoyl dihydrocinchona alkaloid) (0.08 mmol) in toluene (10 mL) was introduced 9-chloromethylanthracene (19.5 mg, 0.09 mmol). The mixture was then refluxed for 15 h. The solution was then cooled to room temperature, concentrated to about 2 mL and poured onto diethyl ether. The precipitate was filtered, washed with diethyl ether and dried to afford the polymers **31–34**.

Poly(4-vinylbenzoyl N-9-methylanthracenyl dihydrocinchoninium chloride) **31**. Yield: 92%;^{1}H NMR: δ 8.54 (m, 2H),

7.57 (m, 7H), 7.49 (m, 5H), 7.34 (m, 4H), 7.16 (m, 7H), 3.86 (m, 2H), 2.95 (m, 1H), 2.05–1.54 (m, 5H), 1.27 (m, 6H), 0.41 (m, 3H); IR ($CHCl_3$): 3460, 1722, 1076 cm^{-1}.

Poly(4-vinylbenzoyl N-9-methylanthracenyl dihydrocinchonidinium chloride) **32**. Yield: 90%; ^1H NMR: δ 8.66 (m, 3H), 7.88 (m, 6H), 7.53 (m, 4H), 7.53 (m, 4H), 7.29 (m, 8H), 3.37 (m, 2H), 2.75 (m, 1H), 2.05 (m, 1H), 1.66 (m, 4H), 1.12 (m, 5H), 0.42 (m, 4H); IR ($CHCl_3$): 3437, 1731, 1089 cm^{-1}.

Poly(4-vinylbenzoyl N-9-methylanthracenyl dihydroquininium chloride) **33**. Yield: 88%; ^1H NMR: δ 9.27 (m, 1H), 8.52–8.10 (m, 5H), 8.06 (m, 2H), 8.02–7.50 (m, 9H), 7.43–7.34 (m, 5H), 3.89 (s, 3H), 3.09 (m, 2H), 2.73 (m, 4H), 1.94–1.17 (m, 7H), 0.98–0.19 (m, 4H); IR ($CHCl_3$): 3270, 2350, 1737, 1519, 1179 cm^{-1}.

Poly(4-vinylbenzoyl N-9-methylanthracenyl dihydroquinidinium chloride) **34**. Yield: 89%; ^1H NMR: δ 9.44 (m, 1H), 8.49 (m, 3H), 8.14 (m, 2H), 8.07 (m, 5H), 7.95–7.60 (m, 4H), 7.54–7.41 (m, 5H), 3.89 (s, 3H), 3.11 (m, 2H), 2.82 (m, 4H), 1.98–1.20 (m, 6H), 0.98–0.15 (m, 5H); IR ($CHCl_3$): 3270, 2954, 2523, 1731, 1504, 1263, 1084 cm^{-1}.

O-9-(4-methylpolystyrenyl)-N-9-anthracenylmethyl cinchona idinium chloride **37–40**
To a solution of sodium hydride 95% (5.3 mg, 0.22 mmol) in DMF (10 mL) was added *N*-9-anthracenylmethyl cinchona idinium chloride at 22 °C (0.22 mmol). The resulting mixture was stirred for 10 min. Merrifield resin (1% DVB, 200–400 Mesh, 1.7 mmol g^{-1}, 141 mg, 0.24 mmol or 1.5% DVB, 2 mmol g^{-1}, 120 mg, 0.24 mmol) was added, and the mixture was stirred under nitrogen at 22 °C for 5 days. The solution was then filtered and washed successively with methanol, THF/water: 1/1, water, dichloromethane, acetone, methanol, and dried in vacuo (20 mmHg) for 1 day, affording a yellow resin.

O-9-(4-methylpolystyrenyl)-N-9-anthracenylmethyl cinchoninium chloride **37**. Yield: 84%; IR (KBr): 3381, 3026, 2924, 1601, 1453, 1018, 760, 701 cm^{-1}; Anal. Calcd for f_{max}: N, 4.76 Found: N, 4.00; loading = 1.43 mmol g^{-1}.

O-9-(4-methylpolystyrenyl)-N-9-anthracenylmethyl cinchonidinium chloride **38**. Yield: 90%; IR (KBr): 3336, 3025, 2924, 1602, 1493, 1452, 1263, 1028, 700 cm^{-1}; Anal. Calcd for f_{max}: N, 4.76 Found: N, 4.28; loading = 1.53 mmol g^{-1}.

O-9-(4-methylpolystyrenyl)-N-9-anthracenylmethylquininium chloride **39**. Yield: 69%; IR (KBr): 3222, 2913, 1940, 1714, 1505, 1175, 704 cm^{-1}; Anal. Calcd for f_{max}: N, 4.75 Found: N, 3.28; loading = 1.17 mmol g^{-1}.

O-9-(4-methylpolystyrenyl)-N-9-anthracenylmethyl quinidinium chloride **40**. Yield: 71%; IR (KBr): 3341, 2900, 1942, 1705, 1678, 1482, 1184, 1005, 704 cm^{-1}; Anal. Calcd for f_{max}: N, 4.75 Found: N, 3.38; loading = 1.21 mmol g^{-1}.

Synthesis of SynPhase™ lantern-supported catalyst **42**
The synthetic procedure used for catalysts 37–40 was applied with a SynPhase™ lantern (80 mg, 0.44 mmol $Cl \cdot g^{-1}$). The lantern was suspended in the reaction mixture through a teflon yarn. Yield: 64%; Anal. Calcd for f_{max}: N, 1.41 Found: N, 0.90; loading = 0.28 mmol g^{-1}.

Synthesis of MeO-PEG$_{5000}$ O-bound N-anthracenyl cinchona alkaloids ***43–46***
Ether linkage **43** *and* **44**: To a mixture of sodium hydride (4.61 mg, 0.192 mmol) in dry DMF (50 mL) was added the *N*-anthracenyl cinchona alkaloid (0.192 mmol) at 22 °C. The resulting mixture was stirred for 10 min. MeO-PEG$_{5000}$-*O*-p$ClCH_2$Bz (990 mg, 0.192 mmol) was added, and the mixture was stirred under nitrogen at 22 °C for 5 days. The mixture was filtered, washed with diethyl ether and dried under vacuum for 1 day.

MeO-PEG$_{5000}$ O-bound N-anthracenyl cinchoninium chloride **43**. Yield: 89%; IR ($CHCl_3$): 2887, 2693, 1959, 1715, 1469, 1100, 844 cm^{-1}; ^1H NMR: δ 8.80 (m, 3H), 8.17 (m, 3H), 7.76 (m, 2H), 7.47 (m, 2H), 7.25 (m, 8H), 7.07 (m, 1H), 5.42 (m, 1H), 5.19 (m, 1H), 4.90 (m, 1H), 4.61 (s, 2H), 4.48 (m, 2H, PEG), 3.63 (PEG), 2.55 (m, 2H), 2.16 (m, 2H), 1.88 (m, 1H), 1.12 (m, 1H).

MeO-PEG$_{5000}$ O-bound N-anthracenyl cinchonidinium chloride **44**. Yield: 90%; IR ($CHCl_3$): 2893, 2693, 1970, 1720, 1454, 1061, 844 cm^{-1}; ^1H NMR: δ 8.81 (m, 3H), 8.39 (m, 3H), 7.94 (m, 2H), 7.43 (m, 2H), 7.27 (m, 8H), 7.09 (m, 1H), 6.04 (m, 1H), 5.05 (m, 1H), 4.67 (m, 1H), 4.31 (s, 2H), 4.13 (m, 2H, PEG), 3.57 (PEG), 2.83 (m, 2H), 1.97 (m, 2H), 1.35 (m, 1H), 1.12 (m, 1H).

Ester linkage **45** *and* **46**: To a mixture of terephtaloyl chloride (38.8 mg, 0.192 mmol) in dichloromethane (50 mL) was added MeO-PEG$_{5000}$-OH (960 mg, 0.192 mmol) and triethylamine (14.1 μL, 0.192 mmol) at 0 °C. The mixture was refluxed for 15 h. After cooling to 0 °C, *N*-anthracenyl cinchona alkaloid (0.192 mmol) and triethylamine (14.1 μL, 0.192 mmol) were added to the solution, which was refluxed for 15 h. The solution was then cooled, concentrated to about 5 mL and poured onto 100 mL of diethyl ether. The polymer was collected by filtration and dried under vacuum at 50 °C for 1 day.

MeO-PEG$_{5000}$ O-bound N-anthracenyl cinchoninium chloride **45**. Yield: 90%; IR ($CHCl_3$): 2873, 2693, 1970, 1720, 1469, 1279, 842 cm^{-1}; ^1H NMR: δ 8.06 (m, 3H), 7.96 (m, 2H), 7.93 (m, 1H), 7.54 (m, 2H), 7.35 (m, 2H), 7.19 (m, 8H), 6.84 (m, 1H), 5.95 (m, 1H), 5.41 (m, 1H), 5.18 (m, 1H), 4.41 (m, 2H, PEG), 3.57 (m, PEG), 2.11 (m, 2H), 1.77 (m, 2H), 1.18 (m, 2H).

MeO-PEG$_{5000}$ O-bound N-anthracenyl cinchonidinium chloride **46**. Yield: 90%; IR ($CHCl_3$): 2889, 2693, 1962, 1715, 1469, 1279, 842 cm^{-1}; ^{1}H NMR: δ 8.17 (m, 3H), 8.11 (m, 2H), 7.67(m, 3H), 7.33 (m, 2H), 7.22 (m, 8H), 6.73 (m, 1H), 5.85 (m, 1H), 5.41 (m, 1H), 5.12 (m, 1H), 4.41 (m, 2H, PEG), 3.57 (m, PEG), 2.14 (m, 2H), 1.67 (m, 2H), 1.19 (m, 2H).

Polymer-bound (O-6′)-connected phase-transfer catalysts **47**

To a solution of sodium hydride 95% (10.8 mg, 0.429 mmol) in DMF (10 mL) was added cupreine hydrochloride (75.0 mg, 0.214 mmol) at room temperature under nitrogen atmosphere. The mixture was stirred for 15 minutes and Merrifield resin (1.7 mmol Cl/g, 1% DVB, 126 mg, 0.214 mmol) was added to the solution. After 5 days of moderate agitation, the reaction was quenched with water (2 mL). The polymer was then filtered, washed with methanol, dichloromethane, acetone and methanol, and dried under reduced pressure at 50 °C for 6 h (Yield: 80%); IR (KBr) : 3024, 2922, 1942, 1601, 1493, 1453, 1266 cm^{-1}.

To a solution of *O*-6′-(4-methylpolystyrenyl) dihydrocupreine (56.6 mg, 0.08 mmol) in toluene (10 mL) was added 9-chloromethylanthracene (58.9 mg, 0.230 mmol) and the mixture was refluxed for 4 days. The polymer was then obtained by filtration, washed with methanol, THF, water, acetone, dichloromethane, methanol, and dried in vacuo (20 mmHg).

O-6′-(4-methylpolystyrenyl) N-9-methylanthracenyl dihydrocupreinium chloride **47**. Yield: 25% (w/w); IR (KBr): 2869, 1953, 1546, 1356, 1103, 702 cm^{-1}.

Polymer-bound (C-11)-connected phase-transfer catalysts **50** *and* **51**

Under argon, n-butyllithium (114 μL, 2.5 M in hexane, 0.285 mmol) was added dropwise to a solution of 10,11-didehydro *O*-9-benzyl-*N*-9-methylanthacenyl cinchona idinium bromide **48** or **49** (0.26 mmol) in THF (5 mL) at −78 °C. The mixture was stirred at −78 °C for 15 min, warmed to 0 °C, and stirred for further 15 min. Merrifield polymer (1.7 mmol Cl $\cdot$ g^{-1}, 1% DVB, 200–400 mesh, 152 mg, 0.26 mmol) was added and the solution was stirred for 5 days at room temperature. The polymer was obtained by filtration, washed with methanol, THF, water, acetone, dichloromethane and methanol and dried in vacuo (20 mmHg).

11-(4-methylpolystyrenyl)-10,11-didehydro O-9-benzyl-N-9-methylanthracenyl cinchoninium bromide **50**. Yield: 31%; IR (KBr): 3058, 2922, 1942, 1874, 1800, 1716, 1601, 1453, 1266, 1027, 755 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 1.74; loading = 0.53 mmol g^{-1}.

11-(4-methylpolystyrenyl)-10,11-didehydro O-9-benzyl-N-9-methylanthracenyl cinchonidinium bromide **51**. Yield: 34%; IR (KBr): 3024, 2912, 1942, 1874, 1801, 1738, 1600, 1453, 1267, 1028, 754 cm^{-1}; Anal. Calcd for f_{max}: N, 5.60 Found: N, 1.90; loading = 0.58 mmol g^{-1}.

Benzylation of N-diphenyl methylene glycine t-butyl ester **9**

To a mixture of **9** (50 mg, 0.166 mmol), *O*-9-(4-methylpolystyrenyl)-*N*-9-anthracenylmethyl cinchonidinium chloride **38** (10 mg, 0.017 mmol) and cesium hydroxide monohydrate (83.6 mg, 0.458 mmol) in toluene (1 mL), was added benzyl bromide (100 μL, 0.847 mmol), dropwise at −50 °C. The mixture was stirred vigorously for 30 h (the reaction was monitored by TLC: dichloromethane). The mixture was then filtered in order to recover the polymer, diluted in ethyl acetate, washed with water, $NaHCO_3$ sat, dried over $MgSO_4$, filtered and concentrated. Purification of the residue by flash chromatography (dichloromethane/triethylamine: 99/1) afforded the (*S*)-α-benzyl *tert*-butylglycinate benzophenone imine as a colorless oil in 67% yield with 94% ee. The enantioselectivity was determined by chiral HPLC (Chiralcel OD-H column, 0.5% 2-propanol, heptane, 1 mL.min^{-1}, λ = 254 nm, 22 °C, retention times: *R* (minor): 10.4 min, *S* (major): 18.1 min. The recycling of the polymer-bound phase-transfer catalyst consists of several washings with MeOH, THF, H_2O, acetone, and CH_2Cl_2/MeOH, then a drying in vacuo (20 mmHg), and a reuse in the next reaction.

2-(Benzhydrylidene-amino)-3-phenyl-propionic acid tert-butyl ester **10**. Yield: 67%; ^{1}H NMR: δ 7.57 (d, J = 7.2 Hz, 2H), 7.51–7.25 (m, 6H), 7.19–7.15 (m, 3H), 7.06 (d, J = 7.6 Hz, 2H), 6.59 (d, J = 6.3 Hz, 2H), 4.10 (dd, J = 9.3, 4.4 Hz, 1H), 3.23 (dd, J = 13.3, 4.3 Hz, 1H), 3.17 (dd, J = 13.3, 9.3 Hz, 1H), 1.44 (s, 9H); ^{13}C NMR: δ 170.8, 170.3, 139.6, 138.4, 136.4, 132.4, 130.1, 129.9, 128.7, 128.2, 128.0, 127.9, 127.7, 126.1, 81.1, 67.9, 39.6, 28.0; IR (film) : 3061, 3028, 2978, 2930, 1737, 1733, 1623, 1495, 1446 cm^{-1}.

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